



UNITED STATES AIR FORCE RESEARCH LABORATORY

A LANDING TASK INVESTIGATION INVOLVING HAPTICS IN A CAVE ENVIRONMENT

Daniel W. Repperger

HUMAN EFFECTIVENESS DIRECTORATE
CREW SYSTEM INTERFACE DIVISION
WRIGHT-PATTERSON AFB, OHIO 45433-7022

**R. H. Gilkey
R. Green**

SCHOOL OF PSYCHOLOGY
WRIGHT STATE UNIVERSITY
DAYTON, OHIO 45435

**Tobias C. LaFleur
Michael W. Haas**

HUMAN EFFECTIVENESS DIRECTORATE
CREW SYSTEM INTERFACE DIVISION
WRIGHT-PATTERSON AFB, OHIO 45433-7022

20011120 055

MARCH 2001

INTERIM REPORT FOR THE PERIOD SEPTEMBER 1999 TO MARCH 2001

Approved for public release; distribution is unlimited.

Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB OH 45433-7022

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Please do not request copies of this report from the Air Force Research Laboratory. Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with the Defense Technical Information Center should direct requests for copies of this report to:

Defense Technical Information Center
8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, Virginia 22060-6218

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2001-0105

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



MARIS M. VIKMANIS
Chief, Crew System Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 074-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 2001	3. REPORT TYPE AND DATES COVERED Interim Report, September 1999 to March 2001	
4. TITLE AND SUBTITLE A Landing Task Investigation Involving Optics in a CAVE Environment			5. FUNDING NUMBERS C: PE: 62202F PR: 7184 TA 38 WU 08	
6. AUTHOR(S) Daniel W. Repperger *R. H. Gilkey *R. Green Tobias C. LaFleur Michael W. Haas				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Human Effectiveness Directorate Crew System Interface Division Air Force Materiel Command Wright-Patterson AFB OH 45433-7022			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Human Effectiveness Directorate Crew System Interface Division Air Force Materiel Command Wright-Patterson AFB, OH 45433-7022			10. SPONSORING / MONITORING AGENCY REPORT NUMBER AFRL-HE-WP-TR-2001-0105	
11. SUPPLEMENTARY NOTES *Wright State University School of Psychology, Dayton, Ohio 45435				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 Words) An experiment was conducted in which subjects had to land a simulated F-16 aircraft using a CAVE (Cave Automatic Virtual Environment) facility, a three-dimensional virtual environment room consisting of multiple mirrors, 3-D video-projected displays in a highly stressful environment. This performance study was accomplished when the six subjects had a haptic stick (force reflecting joystick) condition being either on or off. The tracking mission studied herein also had the constraint that the participants were required to land the aircraft in only one attempt. During the data collection, the visual scene was partially obscured by clouds in the early part of the mission, thus reducing the available visual field. Hence, it was hypothesized that the subjects may benefit more from sensory information provided by the haptic manipulandum when the visual field was reduced. The main results of this study indicate that performance can be enhanced in the CAVE by the haptic condition. One negative aspect of this study was that the CAVE scenario was found to be so extremely compelling that in two situations, subjects could not complete the experiment due to simulator-induced sickness instigated by their exposure to the highly immersive visual field which became quite overwhelming.				
14. SUBJECT TERMS Haptic Stick Controllers, CAVE Environment, Immersive Human-Machine Interfaces			15. NUMBER OF PAGES 38	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UNLIMITED	

THIS PAGE INTENTIONALLY LEFT BLANK

PREFACE

An experiment was conducted in which subjects had to land a simulated F-16 aircraft using a CAVE (Cave Automatic Virtual Environment) facility, a three dimensional virtual environment room consisting of multiple mirrors, 3-D video-projected displays in a highly stressful environment. This performance study was accomplished when the six subjects had a haptic stick (force reflecting joystick) condition being either on or off. The tracking mission studied herein also had the constraint that the participants were required to land the aircraft in only one attempt. During the data collection, the visual scene was partially obscured by clouds in the early part of the mission, thus reducing the available visual field. Hence, it was hypothesized that the subjects may benefit more from sensory information provided by the haptic manipulandum when the visual field was reduced. The main results of this study indicate that performance can be enhanced in the CAVE by the haptic condition. One negative aspect of this study was that the CAVE scenario was found to be so extremely compelling that in two situations subjects could not complete the experiment due to simulator-induced sickness instigated by their exposure to the highly immersive visual field which became quite overwhelming.

TABLE OF CONTENTS

INTRODUCTION.....	1
Literature Review	1
Pertinent Related Research for the Performance Task.....	7
Objectives.....	8
Hypothesis	8
METHODS.....	9
Subjects	9
Apparatus – the CAVE Facility	9
Experimental Procedures.....	11
The Performance Task	11
Haptic and Thrustmaster Sticks.....	13
Experimental Design	17
Training	19
Instruction Set Given to Subjects	21
Subjective Assessment	22
Data Analysis	22
RESULTS	23
DISCUSSION	27
Effects of Haptics versus Difficulty	27
Effects of Difficulty versus Turbulence	28
Effects of Haptics versus Turbulence.....	28
CONCLUSIONS	29
Acknowledgments.....	29
REFERENCES	30
APPENDIX A – Subjective Assessment Questionnaire	33

LIST OF FIGURES

Figure 1. Diagram of CAVE Facility	3
Figure 2a. Top View of Visual Rendering System for CAVE.....	4
Figure 2b. Side View of Visual Rendering System for CAVE.....	4
Figure 3a. Subject in CAVE Environment.....	5
Figure 3b. Subject in Tracking Scenario.....	5
Figure 4. Stereoscopic Viewing to Produce 3-D Image to Subject.....	6
Figure 5a. Training Conditions (No Clouds or Turbulence).....	12
Figure 5b. Data Collection Runs – 1 Day (Full Cloud Condition)	12
Figure 6. Landing Scenario on the Right Runway	14
Figure 7. Performance Metrics Considered at Landing	15
Figure 8. Haptic Stick Force Reflection Algorithm	16
Figure 9. Normalized F-16 Landing Performance Variables	25

LIST OF TABLES

Table I - Training Table - No Clouds - Full Visual Field (Pos.=Initial Position).....	20
Table II - A Possible Set of Runs in the Clouds (Reduced Visibility) Conditions	21
Table III – ANOVA Results for Various CAVE-Haptic Tasks (p levels)	24
Table IV – ANOVA Results for Various CAVE-Haptic Tasks (p levels).....	26
Table V – ANOVA Results for Various CAVE-Haptic Tasks (p levels)	27

THIS PAGE INTENTIONALLY LEFT BLANK.

INTRODUCTION

Synthetic environments provide a valuable forum to immerse the user into a virtual reality computer application to such a degree as to offer perceptual power, which may compensate for the fact that an operator has to perform a task at a remote location. Traditional user interfaces are two-dimensional and some loss of immersive fidelity may arise due to distractions and other confounding variables that compete for sensory modality attention. A CAVE, however, is an interactive, real time, three-dimensional visual/audio/haptic environment, which extrapolates and expands the immersive properties of such synthetic environments to a novel degree. With the appropriate high-resolution visual display, auditory, and haptic rendering, the goal is to provide to the user a higher sense of presence about a remote environment. A subject immersed in the virtual world of a CAVE can be overwhelmed by its commanding size and its 3-D rendered visual scene which utilizes stereoscopic surrounding view (with perspective correction) working with other senses, in harmony, to emulate a synthetic world from the standpoint of the virtual visitor's eyes, ears, and hands. To resolve and create the compelling 3-D view, the subject wears stereoscopic glasses to turn the projections (overlap of two images) into hologram-like images.

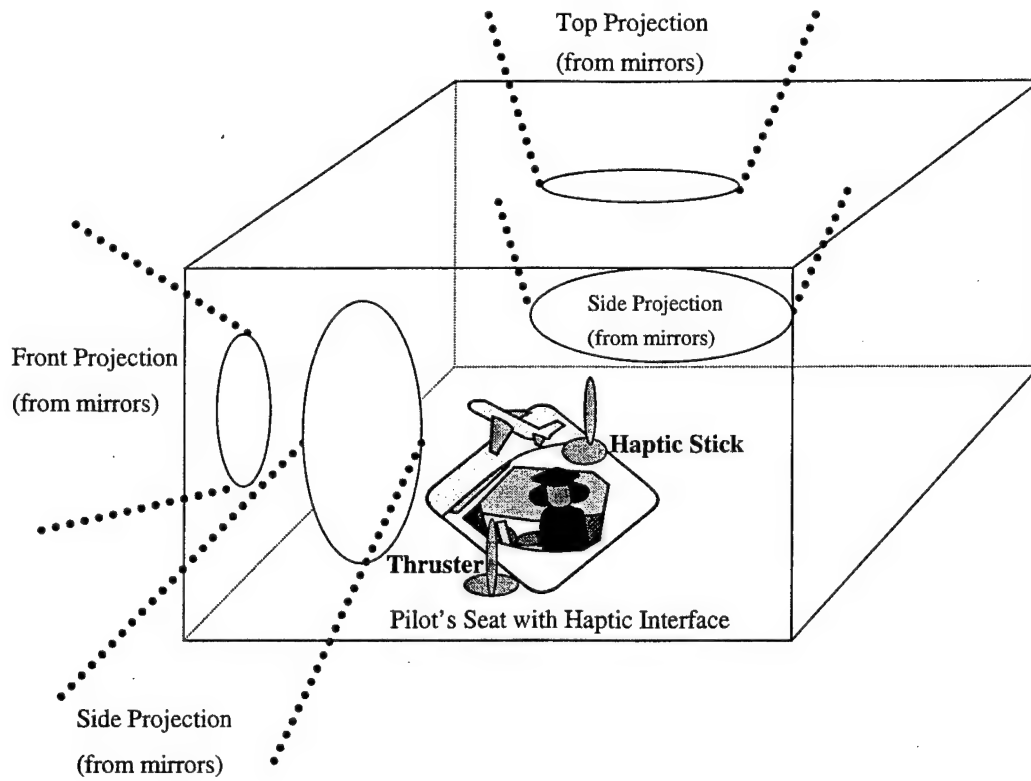
Literature Review

Over thirty-five years ago the concept of an Ultimate Display was discussed (Sutherland, 1965) in which each of the senses would be stimulated in order to provide a complete immersion of the operator into a virtual world. Some synthetic environments of this type, however, may not be practical unless they impart some benefit to performance

for specific tasks. The development of a CAVE is a generalization of traditional two-dimensional display systems and can be attributed to the early work at the University of Illinois at Chicago (Cruz-Neira et al., 1992, 1993). The first systems consisted of four, large rear-projection displays to form walls on a 10-foot cube. A front and two sidewall projections are rendered with a floor projection realized by a ceiling system (Figures 1-2). All views are reflected off single surface, silvered, mirrors excited by a rear projector. It is necessary to provide 3-D visual images and appropriate depth perception. These views are constructed by the overlap of two images and then resolved to the observer via a stereoscopic display and the use of lightweight 3-D LCD shutter glasses (cf. Figures 3a-b). It is also necessary to provide the proper perspective realization for distance correction and to maintain a location and orientation vector of the forehead of the user.

An alternative means of providing improved immersion over 2-Dimensional presentations includes studies in head mounted displays (HMD), which has been a useful means for enhancing fidelity (Durlach and Mavor, 1995). In these systems, the left- and right-eye images are generated on separate displays and directly placed in front of the eyes, or somehow fed through optics to appear in front of the eyes (Figure 4). Some of the difficulties with HMDs, however, include having to deal with the latency of both the image updating and monitoring of head position. Such a system also produces strain on the neck muscles with continued operation. The CAVE overcomes these two drawbacks to the HMD (i.e. latency and fatigue) at the expense of physical space and portability. The main attribute of the CAVE, over traditional interactive synthetic environments, is that it provides even greater immersion properties. Improving presence (defined as a strong impression or feeling that you are at the remote environment) can be achieved via

Fig. 1 - Diagram of CAVE Facility



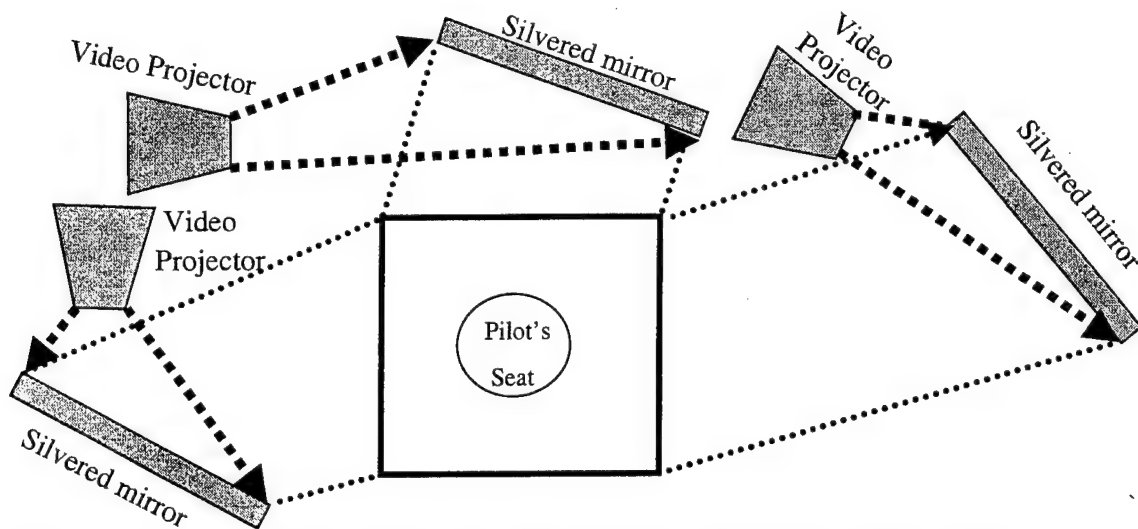


Fig. 2a - Top View of Visual Rendering System for CAVE

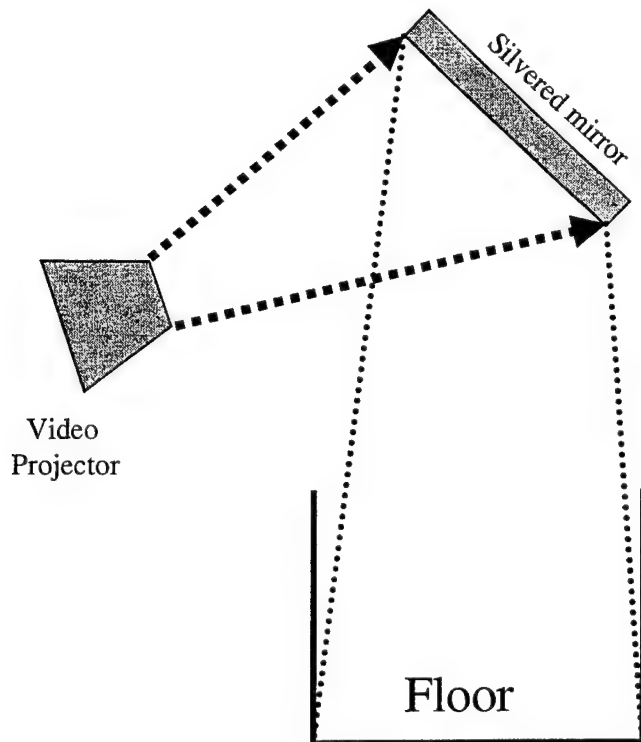


Fig. 2b - Side View of Visual Rendering System for CAVE

Figure 3a - Subject in CAVE Environment



Figure 3b - Subject in Tracking Scenario



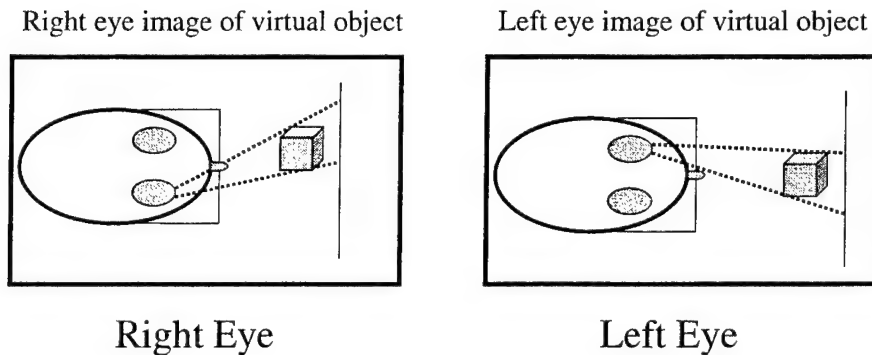


Figure 4. Stereoscopic Viewing to Produce 3-D Image to Subject

gleaning information from alternative sensory modalities. Part of the definition of virtual reality has as its goal the creation of a believable representation of some actual phenomenon. Presently, CAVE facilities exist at a number of research organizations and universities performing exploratory investigations. Some of the studies include the designing of the interiors for automobiles, inspection of dangerous areas such as inside boilers, for studying molecular docking (i.e. finding how molecules bind together), for educational purposes, and also for certain psychological studies (e.g. mitigation of phobias, etc.).

Pertinent Related Research for the Performance Task

A major cause of aircraft accidents can be attributed to tight landing conditions and turbulence manifested by wind shear, wind burst, or other difficult environmental conditions (Phillips, 1995 a, b, and Mecham & Kong, 1995). Since an increasing number of simulation systems being developed today may involve unmanned air vehicles (e.g. aircraft flown at a remote location with no pilot onboard under control of an operator in a safe environment, (Cupp, 1998)), there necessitates the need to study how remote crew stations may be enhanced to improve the performance of the operator in certain undertakings as well as increasing the operator's presence about the external environment at a significant distance from the mission. Studies involving haptic (including force reflecting joystick interfaces) devices have shown that motor learning can be expedited via kinematic feedback (Schmidt and Young, 1991). Both performance and learning show improvement depending on how subjects locate objects in a spatial sense, (Delmez-De Jager & Schepens, 1995 and Bryant & Lanca, 1995). The response strategies elicited by operators are known to be predicated on sensory-sets or motor-sets, (DeFrancesco & DeSario, 1995).

A prior study of investigating tracking performance with aircraft during difficult landing conditions (Repperger, et al., 1997) demonstrated that by adding certain force characteristics to a joystick, several performance measures were significantly improved when the force condition was active. Such a study was previously conducted in a CAVE-like simulator termed the FITE, which was a precursor to the synthetic environment discussed here. Subjective comments by the pilots in the prior 1997 study indicated that they would tend to "feel the direction of the runway" (via the haptic interface) when

limited visual conditions were available. Thus the level of situational awareness or presence was improved via the haptic interface concerning the remote-tracking scenario, when visual conditions were less than ideal. Haptic interfaces are well known to improve tracking performance when a subject has reduced neuromotor capabilities (Repperger, et al., 1995a,b).

Objectives

The intention of this study was to investigate if similar performance improvements, which occurred in a less compelling virtual environment (Repperger, et al. 1997), may also appear in this new synthetic CAVE surroundings where the degree of immersion is even more pronounced. To summarize the results from the 1997 study, it was shown that the benefits derived using the haptic interface tended to ameliorate performance through the mitigation of lateral landing error (reduced error in landing near a desired touch-down point), producing less subjective workload, and lessening the amount of stick activity in handling the aircraft. It was also noted that the haptic stick seemed to show its efficacy best when the turbulence condition was active. The active, haptic, stick seemed to give the operator a sense of presence about the orientation of the landing path. This study will consider the influence on landing performance of an active haptic stick used in a CAVE environment as stated by the following hypothesis.

Hypothesis

The null hypothesis we wish to reject is that the haptic stick provides no performance advantage (using a variety of dependent measures) in such a difficult task environment.

Thus it is desired to reject:

Ho: Haptic sticks do not influence landing performance in a CAVE environment.

METHODS

Subjects

A total of eight subjects participated in this experiment and data were obtained from the six subjects who were able to complete all the experimental conditions discussed herein. A subject panel from a local contractor for the Wright-Patterson Air Force Base in Ohio, USA provided five of the participants. These adult people were either housewives or students at a local university being employed part time. The compensation for participation in this experiment was about \$6 dollars (US) an hour for their participation. The sixth subject was a US Air Force civil servant.

Apparatus - The CAVE Facility

The CAVE (CAVE Automatic Virtual Environment) is a multi-person 10 foot room-sized, high-resolution 3D video and audio environment, which can be used to provide compelling, immersive virtual environment experiences (Figure 1). This unique facility is the property of Wright State University (Department of Psychology) but is located at Wright Patterson Air Force Base in Dayton, Ohio, USA. In addition to the

scope of the academic investigations, the US Air Force also has the opportunity of performing specific experiments related to military applications. Some of the attributes of the CAVE facility include:

- (1) The visual environment consists of up to 300° surround, plus floors (4 walls) for projection of the landing task to the subjects. The walls are 10 x 10 x 10 foot screens with three rear-projected walls and a top-projected screen for the floor (Pyramid Video, Figures 2a-b). Imagery is created by an SGI (Silicon Graphics, Inc.) Onyx computers with Infinite Reality graphics boards to generate similes that are projected onto the walls and floor. The images are displayed by CRT projectors (M8500, Electrohome). With the addition of the unique fourth wall, this system provides complete immersion in the azimuth dimension (the only non-imaged area being directly overhead) allowing the operator to monitor and interact with the environment to the rear as well as to the sides and the front. To give the illusion of 3D, two alternating images are displayed on each wall at a rate of 96 Hz (48 Hz refresh rate per field, Figures 3a-b).
- (2) Virtual spatialized audio (provided to the subjects via earphones) is also available at this facility but was not used in this investigation.
- (3) Virtual or synthetic objects and real objects are integrated via careful monitoring of the head position of the operator (using a magnetic tracking system employed to follow the position and orientation of the user's head and hand (six degree of freedom Flock of Birds, Ascension Technology)). Stereo images are interpreted by use of LCD shutter glasses (Crystal Eyes, Sterographics) that enable a different image to be displayed to each eye by synchronizing the rate of alternating shutter openings to the screen update rates (Figure 4).

(4) The CAVE has a panoramic view that varies from 180° to 300° depending on the distance of the viewer from the projector screens. One final attribute in this facility includes the user's finger-pinch gestures, which are sensed to provide a means to interact with the virtual environment (PinchGloves, Fakespace, cf. Figure 3a, not used in this investigation).

Experimental Procedures

The subjects trained by practicing an aircraft landing task (four sets of trials as in Figure 5a) with full visual information (no wind turbulence) until 50% or more successes (good landings) were achieved. A data day's run consisted of 24 practice trials (Figure 5a), which were then followed by 24 trials for data collection with the cloud cover condition (Figure 5b). A subject was rerun until he/she had achieved at least 50% success for landings starting in the cloud cover. The Task Position levels (P =1,2, and 3) in Figures 5a-b refer to the initial position of the F-16 and will be described in the sequel.

The Performance Task

The duration of the performance task was fixed to not exceed 120 seconds in length with the objective of landing an F-16 aircraft successfully on a runway. The subject had but one opportunity to perform this task at an optimum landing point designated on the

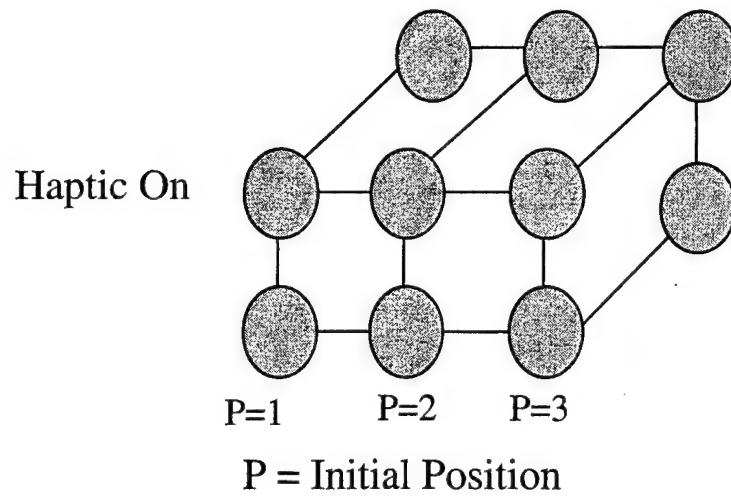


Figure 5a. Training Conditions
(No Clouds or Turbulence)

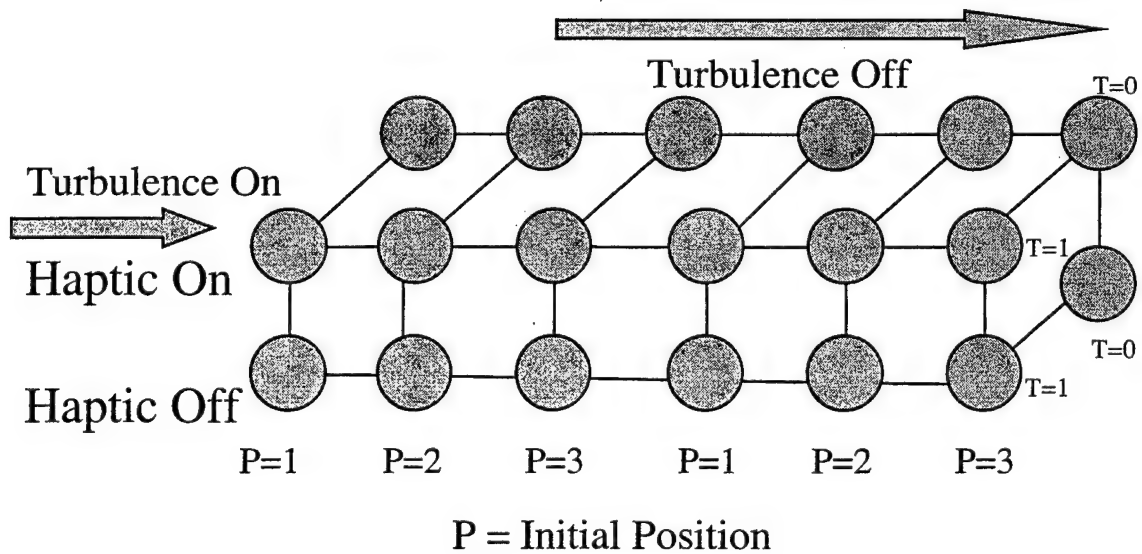


Figure 5b. Data Collection - 1 Day Runs
(Full Cloud Condition)

runway (Figures 6,7). There were three levels of initial position based on the original starting point being aligned with the runway or displaced near or far from the center, to the right or left. Obstacles were located to the right and left of the landing path, as indicated. Sometimes the subjects landed near or off the right runway but such a landing was deemed successful if the weight on wheels at touchdown was considered safe. As indicated in Figure 5b, in half the cases (during data collection), wind turbulence was present. During the data collection, all trials started in the clouds in which the runway could not be initially seen. Subjects were told that they must have the nose of the aircraft pitched upward slightly at landing (3° to 5°). The weight on wheels at touchdown must be distributed on the two back wheels. If a crash occurred, the screen would immediately indicate this event (or a successful landing) and display the negative downward velocity at the touchdown with the forward speed. In Figure 7, the optimum touchdown point would correspond to a zero longitudinal error ($y=0$), zero lateral error ($x=0$), and for the elevation above the runway ($z=6$) feet due to the height of the landing gear.

Haptic and Thrustmaster Sticks

A force-feedback manual control stick (IE-2000, Immersion Corporation) was integrated into the system for manipulating objects and controlling the virtual environment by the right hand of the subject (Figure 3b). Figure 8 illustrates the force reflection algorithm employed. Here the force reflected back on the operator was devised to be a parabolic function of the heading error between the aircraft's body axis and the runway. Such a methodology was employed in the 1997 study (Repperger, et al., 1997)

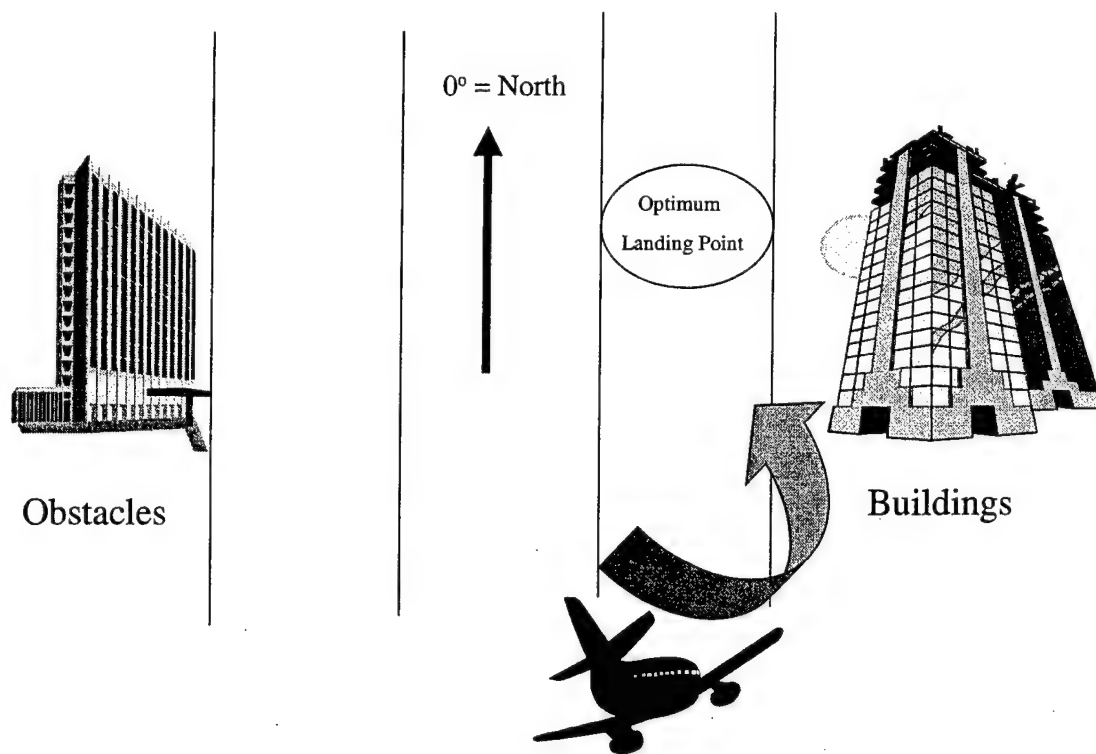


Figure 6. Landing Scenario on the Right Runway

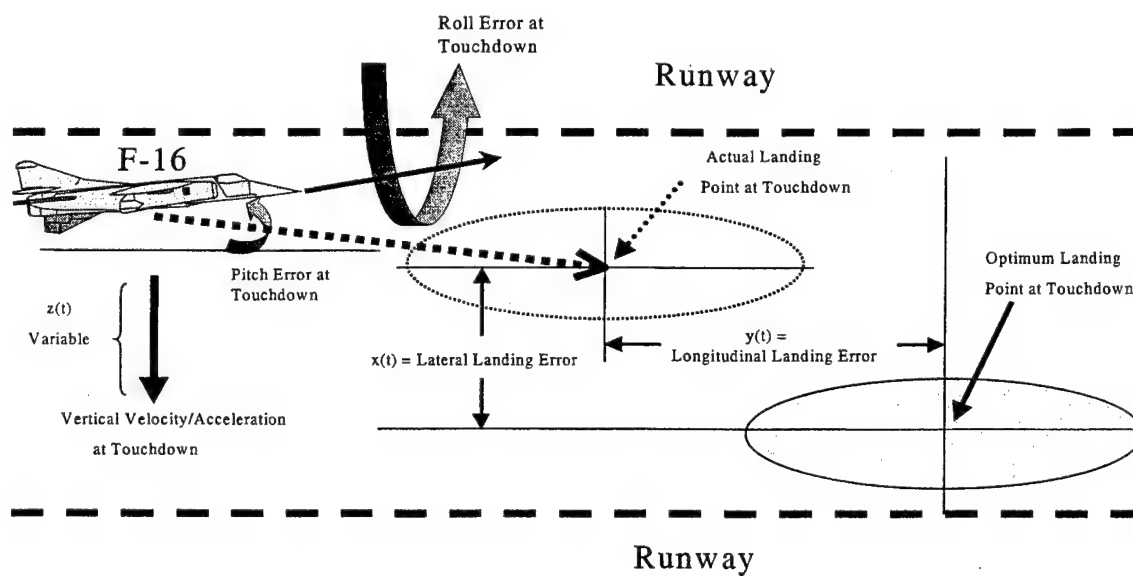


Figure 7. Performance Metrics Considered at Landing

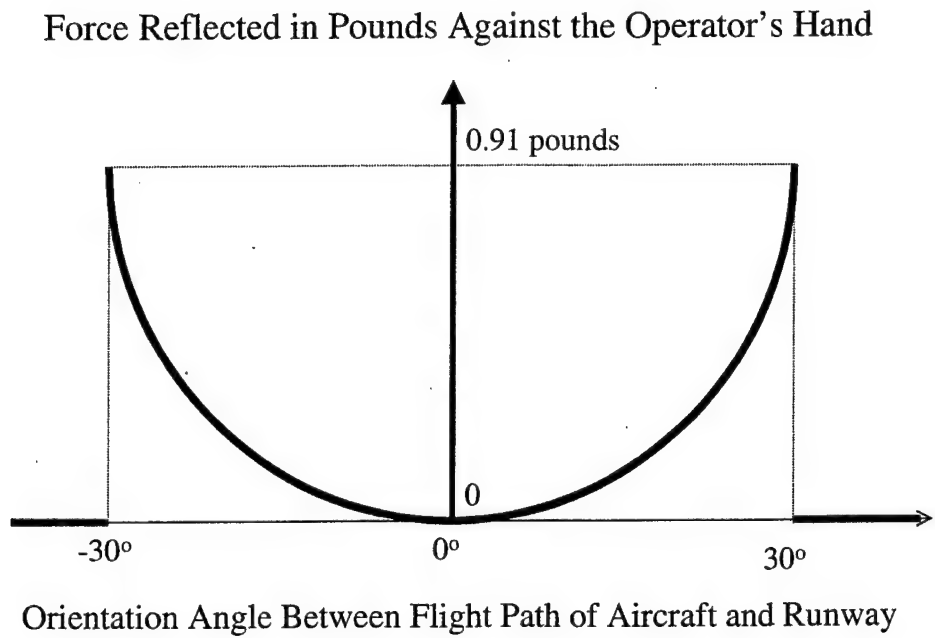


Figure 8. Haptic Stick Force Reflection Algorithm

and had demonstrated efficacy in improving the presence of the operator on the final orientation of the runway when the visual field was partially occluded.

A Thrustmaster joystick was utilized by the subjects with their left hand (Figure 3b) to manipulate aircraft speed. This manipulandum operated as a displacement device with small physical effort required to change its linear position.

Experimental Design

The experimental design was a two-variable, full factorial, and repeated measures. This implies each subject was exposed to all treatment conditions (within subject design, hence each subjects acts as his own control). The first independent variable (two levels) was the haptic stick being either "on" or "off" ("off" corresponds to a displacement stick with no force reflected. The "on" condition for the haptic stick was described previously and represents a haptic algorithm to provide force feedback to the operator, cf. Figure 8). The second independent variable (two levels) was difficulty of the task, which for this analysis consisted of low and high levels of initial position error of the aircraft in relationship to the orientation of the runway. As discussed in the results section, the initial position conditions $P=1$ and $P=2$ were combined into a low difficulty task. The high difficulty task consisted of the conditions $P=3$ for the initial starting points (right or left) of the aircraft. Another variable considered during the data collection was a wind turbulence factor being either high or low. For this task difficulty versus haptics study, all data utilized both levels of the wind turbulence condition but with easy and hard initial starting positions. A variety of dependent performance measures were considered. At landing, the operator had to reach an optimum point "sweet spot" on the runway as

indicated by a green dome on the visual simulation. The root mean square error in the x and y direction from the optimum landing point (denoted as x_{RMS} and y_{RMS}) was calculated when the F-16 aircraft touched down. If these measures were too large, then the landing was not considered successful, since the aircraft was off the runway. Crashes were recorded at landing if too much weight on wheels was determined based on the vertical descent velocity. A metric for calculating crashes was developed from known flight test standards (e.g. an F-16 would be considered crashed if its horizontal velocity, at landing, exceeded 9 ft/sec). Crashes could also occur if the aircraft was out of bounds during touchdown or simply ran out of time and had not landed. A number of other dependent landing performance measures were analyzed including the aircraft's angular rates at landing for both the pitch and roll axis of the aircraft as well as higher derivatives of these position and orientation variables at touchdown.

For both training and data collection, two levels of task difficulty were selected based on varying the initial point of starting the task (i.e. away from the correct alignment of the runway) with the constraint of having a fixed amount of time to land the aircraft. Figure 5a illustrates an experimental design scenario during the training phase. In Figure 5b, the data collection scenario is portrayed. The $P = 1, 2$, or 3 initial starting points were presented randomly to the right or left when the simulation was started. The amount of initial lateral displacement error was either zero, ± 1000 feet, or ± 2000 feet. Preliminary analysis had shown little difference in task difficulty as a consequence of being initially either to the right or left of the runway for the same amount of displacement.

Training

Table I describes the chronological pattern of runs for a typical day's run. Six runs were conducted with the stick being either active (haptic feedback) or passive. The next six runs reversed the condition of the stick. Typically subjects ran this pattern for about fifty minutes and the initial positions were randomized. The next training day the subject ran the initial haptic stick condition being reversed and they continued to practice a pattern similar to Table I.

A critical performance measure was the event of a crash at landing. A crash was defined as having too much weight on wheels as the aircraft landed based on known military standards. A crash would occur if any of the following events happened: (1) The weight on wheels exceeded the maximum allowed, (2) If one back wheel (rather than both back wheels) touched down and the weight on that side of the aircraft exceeded the safe amounts for landing, or (3) If the front wheels should touch down first (with sufficient negative downward velocity/acceleration). Thus for a successful landing, the pitch attitude (orientation) of the aircraft must be slightly nose up (i.e. pitch angle up about 3° to 5°) at landing and not having an excessively large downward velocity/acceleration of the aircraft before the actual touchdown.

If subjects were successful with the training paradigm displayed in Table I, they then moved on to the instrumented flying (i.e. flying in clouds) for data collection. Table II illustrates a typical day's run for data collection for the same haptic condition for 12 runs consisting of two replications of the three initial positions and two turbulence conditions presented randomly. To reach this level of skill it typically took two

additional weeks of practice. Data were not collected and subjects continued to practice until at least 50% successful landings for the Table II trials were achieved.

In the data collection phase in Table II, the cloud condition was initially presented and the subjects had to fly instruments until they broke out of the clouds (at 1.8 nautical miles). After breaking out of the clouds, they had only one chance to land (with about 36 seconds remaining). When the haptic stick condition was active the subjects could “feel” the direction of the runway prior to breaking out of the clouds. If the haptic stick condition was not active, the subjects had no clue as to the direction of the runway and could only sense the lateral displacement error when they immediately broke out of the clouds with their vision. They still had only 1.8 nautical miles to land the aircraft (in about 36 seconds).

Table I - Training Table - No Clouds - Full Visual Field (Pos.=Initial Position)

Haptic on/off	Pos.	Pos.	Pos.	Pos.	Pos.	Pos.
Haptic off	P=3	P=2	P=1	P=3	P=2	P=1
Haptic on	P=1	P=3	P=2	P=2	P=3	P=1
Haptic off	P=2	P=1	P=2	P=3	P=1	P=3
Haptic on	P=3	P=2	P=3	P=1	P=1	P=2

The initial positions P = 1, 2, 3 were presented randomly (with the assistance of a random number generator) so that each subject did not have knowledge as to the initial position he may have had in starting the task. In each set of six runs (same haptic stick condition, cf. Figure 5a), three levels of initial positions occurred twice. The 12 runs during the data collection phase were conducted with the alternative starting stick condition on successive days. This procedure was instigated to mitigate any ordering or fatigue effects.

Table II - A Possible set of Runs in The Clouds (Reduced Visibility) Conditions
(Initial Position: P=1, P=2, P=3, Turbulence = 1 or 0 (on or off))

Haptic Stick	P/T	P/T	P/T	P/T	P/T	P/T
Haptic Off	P=1, T=0	P=2, T=1	P=3, T=1	P=2, T=0	P=1, T=1	P=3, T=0
Haptic Off	P=2, T=1	P=3, T=0	P=1, T=1	P=1, T=0	P=3, T=0	P=2, T=1
Haptic On	P=3, T=0	P=1, T=1	P=2, T=0	P=2, T=0	P=1, T=1	P=3, T=1
Haptic On	P=3, T=1	P=2, T=0	P=1, T=0	P=3, T=1	P=2, T=0	P=1, T=1

Some possible confounding effects may be due to varying reinforcement schedules and inconsistent delivery of critical instructions for subjects that completed the landing tasks. Both the reinforcement schedules and the rules of engagement had to be unswerving across subjects to provide reproducibility. If a subject performed well, he/she was complemented on his/her performance but not given additional instruction. If, however, the subject continued to crash at landing, they were told to focus on the following key points at touchdown to accomplish a successful landing:

Instruction Set Given to Subjects

- (1) Both back wheels should touch first; hence the body axis of the aircraft should be pitched up slightly.
- (2) The air speed should be approximately 180 nautical miles per hour at the landing.
- (3) A gradual angle of approach (small pitch changes) was generally correlated with a successful landing, especially near the ground.
- (4) The negative downward velocity should not be in excess of -5 feet/second at the touchdown.

- (5) The roll angle of the aircraft should be near zero (no wing could touch the ground).
- (6) The speed of the aircraft (left hand control) was not a major factor in a successful landing as long as it was kept near 180 nautical miles/hour.

If the subject still continued to crash at landings, the above six rules were reinforced and practiced until steady-state behavior occurred and the percent of successful landings increased.

Subjective Assessments

At the conclusion of a CAVE run, it was of interest to see if subjects were possibly influenced, in a simulator-sickness sense, by their exposure to this highly immersive visual field rendering. An exit questionnaire was given to the subjects and it is reproduced in Appendix A of this report. Two subjects (out of the eight that started), could not finish the experiment due to simulator-sickness effects.

Data Analysis

At the landing of the F-16 aircraft, which had to be accomplished in one attempt, the data recorded included the key experimental variable conditions (haptic condition on or off, the initial position level, and the turbulence on or off) as well as the important dependent measures: X, Y, and Z landing error with respect to the optimum point, the velocity and acceleration of these variables, the typical aircraft orientation variables (roll, pitch, and yaw), their respective velocities and accelerations, the altitude, position, velocity and acceleration at touchdown and whether a crash occurred. The criteria for a crash would be that a sufficiently high weight of wheels was recorded at touchdown, the

aircraft could be out of bounds, or had an untoward attitude variable recorded at the instant of contact with the ground. The data were analyzed in SYSTAT[®] 8.0.

RESULTS

The risk level that we incorrectly reject the null hypothesis (when H_0 is true) was selected as $\alpha = .05$. This gives a 95% confidence in our decision process. Since this was a within-subjects design, blocking across subjects normally occurred which reduced this source of variation (within a block, however, all other experimental conditions were randomized). We look at the main effects and study their respective interactions.

Six different performance measures are reported here (cf. Figure 7). Since an optimum landing point was displayed, and the actual touchdown point was recorded, this gave rise to the following error variables at touchdown: (1) lateral landing error (X from the optimum point), (2) longitudinal landing error (Y from the optimum point), (3) crash or no crash condition, (4) aircraft Roll error (0° is ideal), (5) pitch error (excessive deviations from the ideal 3° to 5° suggested), and (6) vertical downward velocity/acceleration if this magnitude digressed significantly from the recommended -5 feet/sec velocity at touchdown (-9 ft/sec would constitute a crash).

For all the analyses, the difficulty of the task was first dichomized into two groups. The less difficult task occurred with the initial position at 0° or at a position displaced ± 1000 feet from center. The high level of difficulty considered the ± 2000 feet initial displacement. T-tests were then conducted on the landing variables across both levels of task difficulty with significant differences appearing. Thus the two levels of difficulty were accepted as viable independent variables to perform subsequent analysis.

The first (more general) ANOVA then considered haptics versus task difficulty for the dependent measures consisting of some key landing variables. Table III illustrates significant effects for the normalized dependent measures: crashes X_{RMS} , Y_{RMS} , and $Z_{velocity}$ at the touchdown from this ANOVA. In Table III, the p value and F value are given for the dependent performance measure of interest. The mean values of the variables depicted in Table III are displayed in Figure 9.

Table III – ANOVA Results for Various CAVE-Haptic Tasks (p levels)
(* indicates significant at the $\alpha = .05$ accepted level of risk – Type I error)

Treatment Condition	Crashes (percent)	X – RMS At landing	Y – RMS At landing	Z- Velocity (RMS Value)
Difficulty	p = 0.230 F = 1.603	p < .001* F = 62.536	p = 0.006* F = 10.077	p = 0.289 F = 1.231
Haptics	p = 0.009* F = 9.552	p = 0.003* F = 12.949	p = 0.070 F = 3.793	p = 0.074 F = 3.834
Difficulty * Haptics (Interaction)	p = 0.788 F = .075	p = 0.10 F = 0.880	p = 0.235 F = 1.533	p = 0.445 F = 0.623

To explain the normalization, the percent crashes were determined as a ratio involving the crashes with each block (cf. Table II). The X-RMS values were normalized to one runway width (46 feet). The Y-RMS values were divided by 150 and expressed in feet. The Z values were divided by 9 (negative descent velocity more negative than -9 ft/sec would indicate a crash). Figure 9 illustrates the means of these normalized variables for the corresponding data displayed in Table III. Since both haptics and task difficulty showed main effects but their interactions were not significant ($p > .05$), further analysis of the constituent dependent variables was then conducted. Using a subset of the data from

Table III, a second analysis was accomplished in which it was desired to look within the difficulty and turbulence conditions using some of the above dependent variables including the rotational variables R (roll axis) as well as the vertical descent variable Z (which was related to the occurrence of a crash). Again, a different subset of the data from Table III was then applied in a third analysis in which it was desired to look within the haptics and turbulence conditions using some of the above dependent variables as well as the rotational variables R (roll axis) including the vertical descent variable Z (which was related to the occurrence of a crash).

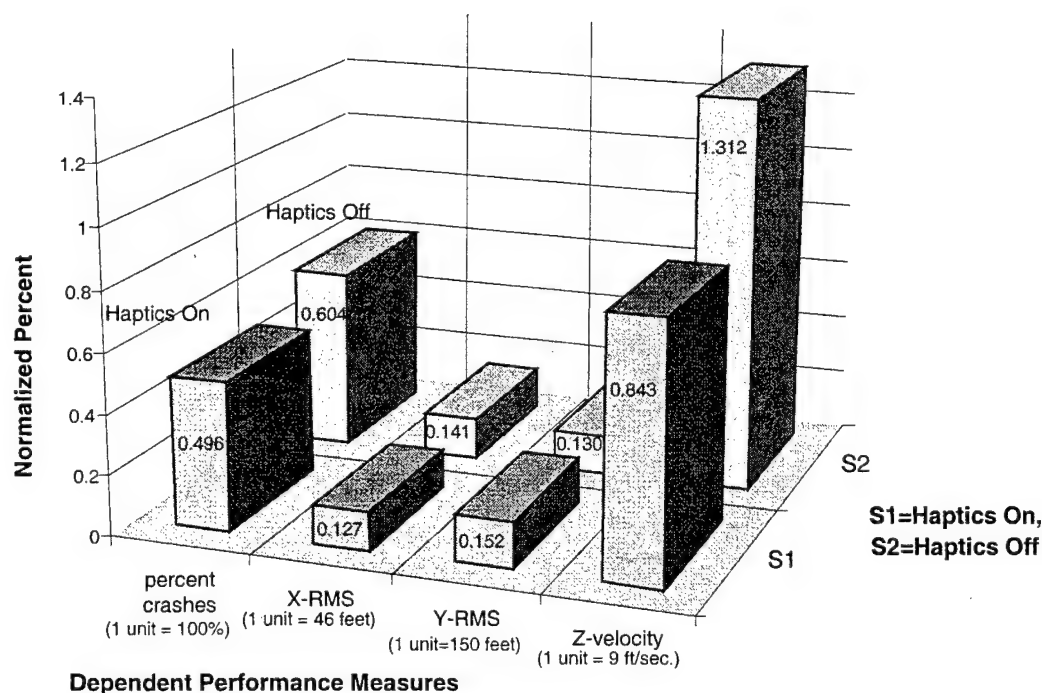


Figure 9. Normalized F-16 Landing Performance Variables

Table IV – ANOVA Results for Various CAVE-Haptic Tasks (p levels)
 (* indicates significant at the $\alpha = .05$ accepted level of risk – Type I error)

Treatment	X-RMS	Y- RMS	R-velocity	R-acceleration
Condition	At Landing	At landing	At landing	At landing
Difficulty	p < 0.01* F = 57.099	p = .014* F = 8.368	p = 0.734 F = 0.121	p = 0.969 F = 0.002
Turbulence	p < 0.01* F = 163.34	P < 0.01* F = 32.665	p = 0.012* F = 8.737	p = 0.016* F = 7.911
Difficulty * Turbulence (Interaction)	p = 0.198 F = 1.861	p = 0.779 F = 0.083	p = 0.991 F = 0.001	p = 0.578 F = 0.326

Table V – ANOVA Results for Various CAVE-Haptic Tasks (p levels)

(* indicates significant at the $\alpha = .05$ accepted level of risk – Type I error)

Treatment	Percent Crashes	X- RMS	Y- RMS	R-velocity
Condition	At Landing	At landing	At landing	At landing
Haptics	p = 0.078 F = 3.721	p = .009* F = 9.848	p = 0.076 F = 3.763	p = 0.196 F = 1.872
Turbulence	p = 0.168 F = 2.158	p < .01* F = 162.899	p < .01* F = 37.977	p = 0.007 F = 10.302
Haptics * Turbulence (Interaction)	p = 0.601 F = 0.288	p = 0.782 F = 0.80	p = 0.430 F = 0.666	p = 0.450 F = .611

DISCUSSION

Effects of Haptics versus Difficulty

From Table III, a number of effects can be gleaned from the data:

The percent of crashes was significantly reduced by the haptics condition being on. To view the results of Table III more clearly, Figure 9 illustrates these key variables with the normalized means of the percent crashes, X_{RMS} , Y_{RMS} and $Z_{velocity}$ displayed. From both Table III and Figure 9, it is obvious that the haptics condition being on significantly reduced the percent of crashes (about 17 percent) when averaged across all other conditions. The X_{RMS} variable was related to performance at landing and both task difficulty and haptics had the proper influence; e.g. greater task difficulty produced higher X_{RMS} at landing. The haptics condition being on reduced the X_{RMS} condition since this error vector and the haptic force reflection algorithm both occurred in the lateral direction. For the Y_{RMS} condition, the haptics condition active did not have a significant reduction. This may be expected since the haptic's effect is orthogonal to the Y direction. For the $Z_{velocity}$ variable, the haptics condition being on did not have a significant effect and difficulty seemed to have a lesser influence. The interaction terms (bottom row of Table III) seem well behaved, except, possibly, for the variable X-RMS. This variable was close to having an interaction ($p=.072$) since both the difficulty measure and haptics occurred in the lateral direction.

Since the main effects are shown in Table III, subsets of these data will now consider specific tests to examine other possible relationships in the data.

Effects of Difficulty versus Turbulence

With reference to Table IV, if the turbulence condition was high, both XRMS and YRMS were affected (when averaged over all difficulty conditions). Also both $|R\text{-velocity}|$ and $|R\text{-acceleration}|$ were higher if the turbulence was high. This seems plausible with an increased turbulence factor, the orientation variable R (R=roll of an aircraft) should be affected. The interactive terms (bottom row of Table IV) showed no major effects since difficulty and turbulence were orthogonal variables that were independent of each other.

Effects of Haptics versus Turbulence

With reference to Table V, when looking within the turbulence data, the percent crashes were not affected (when averaged over difficulty). The variable X-RMS, however, was influenced by both haptics being on and turbulence high. The Y-RMS variable was less affected by the haptics variable but more so by turbulence. The haptic condition worked in a direction that was orthogonal to the Y error. The $|R\text{-velocity}|$ term was affected by turbulence only. This is consistent with Table IV.

CONCLUSIONS

From a performance perspective, certain key landing variables were significantly influenced by the "on" condition of the haptic stick, which was generally in a direction to reduce the lateral touchdown landing error from the optimum point. This worked best and consistently in the same direction that the haptic force was applied (X direction).

A recommendation for future studies would be to activate the haptic stick in both the lateral and longitudinal axis. Also by varying the degree of visual immersion as an independent variable of interest, the benefits provided by the visual field would be better understood in relationship to the haptic manipulandum.

Acknowledgements

The CAVE facilities and computer support for simulation were graciously supplied by Dr. R. H. Gilkey from the Department of Psychology, Wright State University. The data analysis performed was supported, in part, by the AFOSR New World Vista Program, LRIR: 97AL007N11(NWV). The computer simulation support was provided by R. Green. A training paradigm and rule base was developed by T. LaFleur, Ph. D., which significantly helped instruct novice subjects to perform successful landings.

REFERENCES

- Bryant, D. J. & Lanca, M. Spatial concepts and perception of physical and diagrammed scenes. *Perceptual and Motor Skills*, 1995, 81, 531-546.
- Cruz-Neira, C., Sandin, D. J., & Defanti, T. A., Surround-screen projection-based virtual reality: the design and implementation of the CAVE, *Computer Graphics: Proceedings of SIGGRAPH '93*, August 1993, 135-142.
- Cruz-Neira, C., Sandin, D. J., Defanti, T. A., Kenyon, R. V., & Hart, J. C., The CAVE: audio visual experience automatic virtual environment, *Communications of the ACM*, 1992, 35 (6), 65-72.
- Cupp, C. M., Unmanned Aerial Vehicles, The DTIC Review, The Defense Technical Information Center, Vol. 4, No. 2, 1998.
- DeFrancesco, C. & DeSario, L. F., Observation of response strategies in cycling time trials. *Perceptual and Motor Skills*, 1995, 81, 171-188.
- Delmeze-De Jager, D. & Schepens, N. Observation of response strategies in cycling time trials, *Perceptual and Motor Skills*, 1995, 81, 171-188.
- Durlach, N. I. & Mavor, A. S. (Eds.), *Virtual reality – scientific and technological challenges*, Washington DC: National Research Council, National Academy Press, 1995
- Mecham, M & Kong, H., Wind shear blamed in Apstar-2 loss. *Aviation Week and Space Technology*, 1995, 143(13), 38-39.
- Phillips, E. H., FAA offers proactive safety concept. *Aviation Week and Space Technology*, 1995a, 143(18), 42.
- Phillips, E. H., Vortex tests may yield clues to US AIR crash. *Aviation Week and Space Technology*, 1995b. 143(14), 33.
- Repperger, D. W., Phillips, C. A., & Chelette, T. L. Performance study involving a force-reflecting joystick for spastic individuals performing two types of tracking tasks. *Perceptual and Motor Skills*, 1995a, 81, 561-562.
- Repperger, D. W., Haas, M. W., Brickman, B. J., Hettinger, L. J., & Roe, M. M, Design of a haptic stick interface as a pilot's assistant in a high turbulence task environment. *Perceptual and Motor Skills*, 1997, 85, 1139-1154.

- Repperger, D. W., Phillips, C. A., & Chelette, T. L., A study on spatially induced 'virtual force' with an information theoretic investigation of human performance. *IEEE Transactions on Systems, Man, and Cybernetics*, 1995b, 25, 1392-1404.
- Schmidt, R. A. & Young, D. E. Methodology for motor learning: a paradigm for kinematic feedback. *Journal of Motor Behavior*, 1991, 23, 13-24.
- Sutherland, I. E., 1965, The Ultimate Display, *Proceedings of the IFIP Congress*, 1965, 2:506-508.

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX A – Subjective Assessment Questionnaire

**CONSENT TO PARTICIPATE IN RESEARCH
VERITAS FACILITY
DEPARTMENT OF PSYCHOLOGY
WRIGHT STATE UNIVERSITY
DAYTON, OHIO 45435**

The purpose of this research study is to obtain data on auditory, visual and/or haptic performance in virtual environments. These data will be used to guide the design of virtual environment systems that will produce more realistic experiences for users.

During this study, I will sit quietly, while visual images and/or sounds, either stationary or moving, are presented. In response to these stimuli, I will make verbal statements or make gestural motions with my hands. The experimental session will take approximately _____ hours. I understand that I will be compensated at a rate of _____ for my participation.

In some of the experiments, I may be seated inside a virtual environment facility called "the CAVE" composed of four 10x10- foot display screens in the shape of a square room. In some experiments I may see only visual images (on the large display screens and/or the floor, or computer monitors or both) without sound, I may hear sounds (either over headphones or over loud speakers) or I may see images and hear sounds together. I may wear thin cloth gloves to measure my hand gestures (e.g. pinching motions). I may wear liquid crystal (LCD) shutter glasses, like large sunglasses to see 3D images, but can wear these shutter glasses over any eyeglasses or contact lenses I may normally wear. The shutter glasses or headphones may have a commercial magnetic tracking sensor attached to it that is used to measure and record the position of my head. The cloth gloves may have the same type of sensors attached to measure and record the positions of my hands. In some experiments I will use a hand controller or joystick to interact with and control the motion or behavior of objects in the virtual environment.

I understand that any information about me obtained from this study will be kept strictly confidential and that I will not be identified by name in any report or publication.

I realize that I may experience symptoms like motion sickness, similar to what I might experience riding in a car or after a carnival ride. If I experience symptoms, I should immediately inform the experimenter through the intercom. In addition, I will be tested for motion sickness symptoms before and after the experiment. I understand that if the symptoms have not gone away after 1 hour, I will be advised not to drive a car for 24 hours and a ride will be provided. The sounds I hear would never be harmful or uncomfortably loud. If the sounds are uncomfortable, I should immediately remove the headphones and notify the experimenter through the intercom. If viewing the images causes any eye strain, I should immediately notify the experimenter through the intercom.

I realize that participation in this research is completely voluntary. I understand that I am free to refuse to participate in this study or to withdraw at any time. There is no penalty of any kind for either non-participation or withdrawal.

A summary of the results of the experiment may be requested by contacting the researchers listed below. The results of this study will be available on approximately _____.

If I have concerns or questions about the research I understand I can contact the Principal Investigator, Robert H. Gilkey at 775-337 John Flach, Co-Investigator 775-2574 or through the Wright State University, Department of Psychology (775-2391).

My signature below indicates that I consent to participate in this research investigation.

_____ Date _____

Name (Please Print Neatly) _____